THIN-FILM PV MODULE REVIEW

Changing Contribution of PV Module Technologies for Meeting Volume and Product Needs

The world PV module market is projected to reach 12 to 25 GWp by 2015, unless politically mandated solar programs are implemented to achieve even larger, more energy significant production volume. To meet projected volumes at a declining cost expected from markets, it is anticipated that thin-film PV module technologies will contribute at growth rates faster than average industry growth rates, and hence contribute 3.5 to 6 GWp toward such anticipated volume. Bolko von Roedern, NREL, USA reports.

With 1.7 GWp of solar cells/modules fabricated and sold in 2005, and assuming continued demand growth of 25% per year, world demand by 2015 can be expected to exceed 12 GWp. If average annual growth rates of 35% could be maintained, the overall demand could then be near 25 GWp. At an average module efficiency of 15%, this would require 85 to 170 km^2 of flat-plate modules to be produced (a corresponding production rate of 4 to 8 m^2/sec). It is possible that some modest fraction of this requirement could be provided by concentrating PV systems, but looking at current technical realities, concentrator market share can be expected to remain small under a 25% to 35% per year "business as usual" growth scenario.

Given the following quantitative estimates, it becomes clear that the potential for concentrator PV systems lies in a politically mandated penetration of photovoltaics much greater than the projected 12 to 25 GWp. Although this is still a very small number in the context of overall world energy consumption, it nevertheless requires significant changes in operation and significant increases in photovoltaic manufacturing. For example, if this quantity were to be provided by a single PV technology, and based on known material consumption rates (no "breakthroughs"), a capacity of 12 GWp would require 120,000 tons of Si feedstock if for wafer silicon modules, or about 500 tons of indium or tellurium for CIGS or CdTe technology. These numbers, along with observations of current investment activities and the maturity of different technologies, suggest that a changing mix of technologies will deliver the 12 to 25 GWp in 2015. Based on past experience, it is important to base projections for the relative short nine-year time span only on what is known today, with breakthroughs having little or no effect on actual manufacturing in 2015.

Current market status

In 2005, over 90% of the PV modules shipped worldwide were wafer or ribbon silicon technology. It is, however, very noteworthy that already in 2005, 29% of the modules manufactured in the United States were "thin-film" modules, predominantly manufactured by Uni-Solar (a-Si triple junction technology) and First Solar (CdTe technology). These two companies have announced near-term (by 2007) quadrupling or tripling of their current US-based manufacturing capacity, respectively. We believe that this indicates a significant transition to thin-film PV module manufacturing. What is the reason for this transition?

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Crystalline Si PV has become a mature technology. Thus, the typical experience curve (price or cost reduction, which for PV modules until now has typically been 0.8 for each doubling in capacity) can be expected to become shallower, because these experience curves cannot continue indefinitely and obviously will become asymptotic at the materials and manufacturing cost level. This is the fate of any mature technology. Since 2004 price declines in crystalline Si modules have no longer occurred as expected because of Si feedstock shortages and corresponding price increases that added to the cost of manufacturing such modules. Another important point is that wafer-Si PV appears at a crossroads [1]. It is not clear how large a quantity of true high-efficiency cells (commercial cell efficiencies >/20%) and modules (commercial module efficiencies >/17%) can be manufactured. The reason for this uncertainty is that such fabrication requires high-lifetime single-crystal wafers and alternative processes for the junction formation. There are indications that the solar-grade feedstocks developed for the production of cast-multicrystalline wafers are of insufficient quality to allow the growth of single-crystal high-lifetime (>500 microseconds) wafers. It is also of interest to note that the managers of several silicon PV companies (e.g., Sharp, Q-Cells, Schott) have stated that there would be limits to growing their crystalline Si silicon business to beyond 1 GWp/y by simply expanding further. All of these companies are researching wafer-Si alternatives including the traditional thin-film technologies, and in some instances, are already offering such commercial thin-film modules.

Large a-Si triple-junction solar cell roofing laminates made in collaboration between United Solar and Solar Integrated Roofing Technology

New technologies

To drive module cost down further, new technologies have to be employed. In the foreseeable future, only the established thin-film module technologies (amorphous silicon and nanocrystalline Si films (a-Si), cadmium telluride (CdTe), and copper indium/gallium diselenide (CIGS), appear capable of delivering significant module quantities. It is important to develop realistic performance and manufacturing-cost expectations based on what is known today. This requires comparing module performance and manufacturing cost for comparable levels of manufacturing maturity. We are using currently available best commercial products as a baseline and deriving the ratio between current verified champion cell performance [2] (for each specific PV technology) and the total-area commercial module efficiency. Table 1 provides such data for a few selected module types.

Looking at the performance ratio between the commercial product and champion solar cell serves two purposes. First, it provides a reality check as to what commercial performance can be expected based on known solar cell R&D results. Second, it provides a means for gauging how mature a manufacturing process is, with higher percentages indicating higher maturity. To estimate future performance of various PV technologies, it is reasonable to assume that all technologies will achieve a similar degree of manufacturing maturity, and for a variety of reasons, we believe that the best ratio expected to be achievable with low-cost mass-production methods would be 80%. To estimate module production cost, we employ a pragmatic and consistent approach that aims at avoiding distortions in the comparison of the module cost of various PV technologies [2]. In Table 2, we therefore provide future expected module performance levels based on 80% of today's demonstrated champion cell performances. To compare module costs, in column 3 of Table 2 a relative performance is defined by arbitrarily selecting the anticipated efficiency level of the currently dominating standard Si PV technology as 1.

Cost advantages

Conventional cost projections may be either favourable (i.e., aggressive) or less favourable (i.e.,

Eff.(%)	Module	Temp. Coeff. (%P/°C)	Technology	Performance Ratio product/champion-cell
17.7	SunPower SPR220	-0.38	Single-crystal Si non-standard junction	17.7/24.7 = 72%
17.0	Sanyo HIP-200BA3	-0.29	Single-crystal Si non-standard junction	17.0/24.7 = 69%
15.5	BP 7195	-0.5	Single-crystal Si non-standard junction	15.5/24.7 = 63%
14.2	Kyocera KC200GT	V_{OC}=-0.123 V/°C	Multi crystal Si standard junction	14.2/21.2 = 67%
13.3	Shell PowerMax 175-C	-0.43	Single-crystal Si standard junction	13.3/21.2 = 63%
13.2	Schott ASE-300-DGF/50 (320-W_p)	-0.47	EFG (ribbon) Si standard junction	13.2/21.2 = 62%
11.0	WürthSolar WS31050/80	-0.36	CIGS	11.0/19.5 = 56%
7.6	First Solar FS-65	-0.25	CdTe	9.3/16.5 = 56%
6.4	Mitsubishi Heavy MA100	-0.2	a-Si, single junction	6.4/10.0 = 64%
6.4	Uni-Solar ES-124	-0.21	a-Si, triple junction	6.4/12.1 = 53%

Table 1: Module efficiency from survey of manufacturers' websites and "Performance ratios"

Technology	Future commercial module efficiency, based on 2006 technology knowledge (%)	Relative performance rating (Standard, silicon = 1)	Relative cost divided by relative performance (About proportional to future $/Wp module cost differences with standard crystalline Si) assuming 40% thin-film module cost advantage.
Silicon (non-standard)	19.8	1.18	0.85 (more competitive)
Silicon (standard)	17.0	1.00	1.00 (by definition)
CIGS	15.6	0.92	0.65 (highly competitive)
CdTe	13.2	0.78	0.77 (highly competitive)
a-Si (1-j)	8.0	0.47	1.28 (not competitive)
a-Si (3-j)	9.7	0.57	1.05 (about the same)

Table 2: Projected future efficiencies of various commercial module technologies and their relative performance and cost.

realistic). Our method assumes a consistent 40% cost advantage for thin-film modules, based on the knowledge that in a crystalline Si module, typically 40% of the manufacturing costs are incurred by manufacturing the silicon wafer or ribbon required for manufacturing the solar cells. This cost component is minimized, essentially eliminated, in the manufacturing of thin-film modules. Hence, for the thin-film technologies, relative cost levels are deduced by multiplying the inverse of relative performance by 0.6 to account for the avoided cost of wafers (ribbons).

The last column provides relative cost rankings for the various technologies. It suggests that based on anticipated performance levels, non-standard high-efficiency Si modules will provide lower cost/Wp numbers than modules made of the currently dominating technology, standard screen-printed Si cells. CIGS and CdTe modules would be highly competitive with either silicon technology. Lower-efficiency a-Si modules appear to come out about the same as the current standard Si technology. The relative cost numbers listed in column 4 are only for the module itself. In addition, balance of system (BOS) costs must be considered. For standard arrays, these are usually (presently, perhaps $0.5/Wp) higher for lower-efficiency modules. However, if BOS cost can be avoided altogether, for example by installing prelaminated roofing foils as in the case of Uni-Solar, such installation schemes actually generate a BOS credit; presently, estimates are of the order of $0.7/Wp cost reduction for such installations reflecting the avoided installation costs.

To accelerate module sales volumes, it is important that cost and price reductions are maintained. Some detailed studies have suggested that this is much more easily accomplished by transitioning to thin-film module technologies as soon as is feasible [3]. After reviewing press releases and public announcements, we believe that about 1 GWp of "actually producing" annual thin-film module manufacturing capacity may be on line worldwide by the year 2010. Extrapolating another 5 years to 2015, and using more manageable average annual growth rates of 35% to 45% for thin-film technologies for this period, it would appear that of the 12–25 GWp expected to be produced by 2015, 3.5 to 6.5 GWp may be produced as thin-film modules.

German installers of PV fields yearn for low-cost modules, and a number of them have actually adopted the use of glass-superstrate thin-film modules from First Solar (CdTe), Kaneka (a-Si), and Mitsubishi Heavy Industries (a-Si). Our rough estimate suggests that these modules are purchased at a price that is approximately 30% lower than the cost of crystalline Si modules. Balance of systems costs are 10% to 15% higher for the thin-film PV systems, which nevertheless can already today result in an overall reduced system cost.

Future projections

We have now seen a-Si and CdTe module technologies transition to commercial manufacturing operations and successful pilot operations for CIGS. Hence, we believe that all three technologies will contribute to the 2015 production numbers. Looking beyond this point, a concern for unabated further growth of CIGS and CdTe module production arises based on the availability of In and Te, once each of these technologies reaches a production level of greater than 10 GWp [4]. The U.S. PV program currently pursues two approaches to mitigate such production limits caused by feedstock limitations: (a) using less CIGS and CdTe material by developing devices with much thinner absorber layers (thicknesses reduced by a factor of >5); (b) exploring alternate cell structures that would provide the same or higher cell and module efficiencies without using In or Te.

We now have an experience base telling us how long it took to get current PV technologies to where they are today. In today's much improved investment climate, it is of course easier to build large factories that coat large areas of glass or flexible substrates. However, while such factories could be built, costly mistakes can be made if the coatings don't deliver the expected solar conversion efficiencies. We believe that near term, only technologies that have already demonstrated proven module prototypes have a chance to be successful in high-volume manufacturing. Based on what is known today, the performance of organic and dye-sensitized ("Grätzel") cells (and any other new solar cell technology) is no better than traditional alternatives and convincing module prototypes have not been demonstrated. Significant further cell and module development activities are required to ascertain whether these new PV technologies can demonstrate solar cell and module performance that can reach or exceed values given in Table 2 for the established technologies. This seems to be a prerequisite for any new technology to impact PV energy generation.

References

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[4] A. Feltrin and A. Freundlich, ibid